

THERMAL BARRIER COATINGS HAVING LOWER LAYER FOR IMPROVED ADHERENCE TO BOND COAT

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0001] This invention was made with Government support under Contract No. N00421-00-3-0443 awarded by the Office of Naval Research. The Government has certain rights to the invention.

BACKGROUND OF THE INVENTION

[0002] This invention relates to zirconia-containing thermal barrier coatings having reduced thermal conductivity that comprise a stabilizer metal oxide selected from ytterbia, neodymia or mixture thereof, with or without lanthana, to stabilize the zirconia in the cubic crystalline phase. This invention particularly relates to such reduced thermal conductivity coatings having a zirconia-containing lower layer stabilized in the tetragonal phase for improved adherence to the bond coat. This invention further relates to articles having such coatings and methods for preparing such coatings for the article.

[0003] Components operating in the gas path environment of gas turbine engines are typically subjected to significant temperature extremes and degradation by oxidizing and corrosive environments. Environmental coatings and especially thermal barrier coatings are an important element in current and future gas turbine engine designs, as well as other articles that are expected to operate at or be exposed to high temperatures, and thus cause the thermal barrier coating to be subjected to high surface temperatures. Examples of turbine engine parts and components for which such thermal barrier coatings are desirable include turbine blades and vanes, turbine shrouds, buckets, nozzles, combustion liners and deflectors, and the like. These thermal barrier coatings typically comprise the external portion or surface of these components are usually deposited onto a metal substrate (or more typically onto a bond coat layer on the metal substrate for better adherence) from which the part or component is formed to reduce heat flow (i.e., provide thermal insulation) and to limit (reduce) the operating temperature the underlying metal substrate of these parts and components is subjected to. This metal substrate typically comprises a metal alloy such as a nickel, cobalt, and/or iron based alloy (e.g., a high temperature superalloy).

[0004] For reduced thermal conductivity, the thermal barrier coating is usually prepared from a ceramic material, such as zirconia. It is also desirable to chemically phase-stabilize the zirconia-containing thermal barrier coating in the cubic phase. The cubic phase

is desirable for lower thermal conductivity and can be either fluorite or pyrochlore structure. Examples of such chemically phase-stabilized zirconias include yttria-stabilized zirconia, scandia-stabilized zirconia, ceria-stabilized zirconia, calcia-stabilized zirconia, and magnesia-stabilized zirconia. The thermal barrier coating of choice is typically a yttria-stabilized zirconia ceramic coating. A representative yttria-stabilized zirconia thermal barrier coating usually comprises about 7 weight % yttria and about 93 weight % zirconia.

[0005] There a variety of ways to further reduce the thermal conductivity of such thermal barrier coatings. One is to increase the thickness of the coating. However, thicker thermal barrier coatings suffer from weight and cost concerns. Another approach is to reduce the inherent thermal conductivity of the coating. One effective way to do this is to provide a layered structure such as is found in thermal sprayed coatings, e.g., air plasma spraying coatings. However, coatings formed by physical vapor deposition (PVD), such as electron beam physical vapor deposition (EB-PVD), that have a columnar structure are typically more suitable for turbine airfoil applications (e.g., blades and vanes) to provide strain tolerant, as well as erosion and impact resistant coatings.

[0006] Another general approach is to make compositional changes to the zirconia-containing ceramic composition used to form the thermal barrier coating. A variety of theories guide these approaches, such as: (1) alloying the zirconia lattice with other metal oxides to introduce phonon scattering defects, or at higher concentration levels, provide very complex crystal structures; (2) providing “coloring agents” that absorb radiated energy; and (3) controlling the porosity morphology of the coating. All of these approaches have limitations. For example, modifying the zirconia lattice, and in particular achieving a complex crystal structure, limits the potential options for chemical modification and can interfere with good spallation resistance and particle erosion resistance of the thermal barrier coating.

[0007] Modification of the zirconia lattice to improve the reduction in thermal conductivity can also interfer with other mechanical properties of the thermal barrier coating. In particular, modification of the thermal barrier coating to reduce thermal conductivity can result in a coating that is less adherent to the underlying bond coat layer. As a result, the thermal barrier coating can be vulnerable to spallation over time, especially due to temperature cycling that occurs during normal operation of gas turbine engines. Inclusion of a lower layer comprising, for example, yttria-stabilized zirconia can improve adherence of the thermal barrier coating to the bond coat, but at the cost of losing some of the reduced thermal conductivity benefit achieved by changing the compositional parameters of the thermal

barrier coating.

[0008] Accordingly, it would be desirable to be able to change the compositional parameters of the zirconia-containing ceramic composition to achieve further reductions in the thermal conductivity of the resultant thermal barrier coating by being able to stabilize the zirconia in the cubic crystalline phase. It would further be desirable to be able to achieve such reductions in thermal conductivity without sacrificing other desired mechanical properties of the thermal barrier coating, especially good spallation resistance.

BRIEF DESCRIPTION OF THE INVENTION

[0009] An embodiment of this invention relates to a thermal barrier coating for the underlying substrate of articles that operate at, or are exposed to, high temperatures. This thermal barrier coating comprises:

- A. a zirconia-containing upper layer wherein the zirconia is stabilized in the cubic crystalline phase, and which comprises:
 1. at least about 50 mole % zirconia; and
 2. a stabilizing amount up to about 49 mole % of a stabilizer component comprising:
 - a. a first metal oxide selected from the group consisting of ytterbia, neodymia, mixtures of ytterbia and neodymia, mixtures of ytterbia and lanthana, mixtures of neodymia and lanthana, and mixtures of ytterbia, neodymia and lanthana in an amount of from about 5 to about 49 mole %;
 - b. about 4 mole % or less of a second metal oxide selected from the group consisting of yttria, calcia, ceria, scandia, magnesia, india and mixtures thereof; and
 3. one or more of a third metal oxide selected from the group consisting of:
 - a. hafnia in an amount from about 0.5 to about 40 mole %; and
 - b. tantala in an amount of from about 0.5 to about 10 mole %; and
- B. a zirconia-containing lower layer wherein the zirconia is stabilized in the tetragonal crystalline phase, and which comprises:
 1. at least about 80 mole % zirconia; and
 2. a stabilizing amount up to about 10 mole % of a stabilizer component, which comprises:

- a. a first metal oxide selected from the group consisting of yttria, calcia, ceria, scandia, magnesia, india and mixtures thereof in an amount of from about 1.5 to about 6 mole %; and
- b. a second metal oxide selected from the group consisting of lanthana, neodymia, ytterbia and mixtures thereof in an amount of from about 0.5 to about 8.5 mole %.

[0010] Another embodiment of this invention relates to a thermally protected article. This protected article comprises:

- I. a substrate;
- II. a bond coat layer adjacent to and overlaying the substrate; and
- III. the thermal barrier coating previously described adjacent to and overlaying the bond coat layer.

[0011] Another embodiment of this invention relates to a method for preparing the thermal barrier coating on the bond coat layer of the substrate to provide a thermally protected article. This method comprises the steps of:

- A. forming the lower layer of the thermal barrier coating by depositing on the bond coat layer the ceramic composition of B above; and
- B. forming the upper layer of the thermal barrier coating by depositing on the lower layer the ceramic composition of A above.

[0012] The thermal barrier coatings of this invention provide several benefits when formed on bond coat layers of substrates of articles exposed to high temperatures, such as turbine components. The zirconia-containing upper layer of the thermal barrier coating permits the zirconia to be stabilized in the desired cubic phase structure to provide reduced thermal conductivity. The zirconia-containing lower layer which is stabilized in the tetragonal crystalline phase provides improved adherence of the upper layer of the thermal barrier coating to the bond coat layer, thus improving the resistance of the thermal barrier coating to spallation, including that due to temperature cycling that occurs during normal gas turbine engine operation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The FIG. is a partial side sectional view of an embodiment of the thermal barrier coating and coated article of this invention.

DETAILED DESCRIPTION OF THE INVENTION

[0014] As used herein, the term "zirconia-containing ceramic compositions" refers to ceramic compositions where zirconia is the primary component that are useful as thermal barrier coatings that are capable of reducing heat flow to the underlying substrate of the article, i.e., forming a thermal barrier, and which have a melting point that is typically at least about 2600°F (1426°C), and more typically in the range of from about 3450° to about 4980°F (from about 1900° to about 2750°C).

[0015] As used herein, the term "comprising" means various compositions, compounds, components, layers, steps and the like can be conjointly employed in the present invention. Accordingly, the term "comprising" encompasses the more restrictive terms "consisting essentially of" and "consisting of."

[0016] All amounts, parts, ratios and percentages used herein are by mole % unless otherwise specified.

[0017] The ceramic compositions used in the upper layer of the thermal barrier coatings of this invention impart improved thermal conductivity properties and in particular lower thermal conductivity. Thermal conductivity K is defined by the following equation (1):

$$K = \alpha \times (1-p) \times C_p \times D_t \quad (1)$$

where α is the thermal diffusivity, p is the fraction of porosity, C_p is the specific heat (in J/g *K), and D_t is the theoretical density. As be seen from equation (1) above, the thermal conductivity depends on thermal diffusivity and porosity.

[0018] Particularly suitable zirconia-containing ceramic compositions for use in the upper layer of this invention are disclosed in copending U.S. nonprovisional applications entitled "CERAMIC COMPOSITIONS FOR THERMAL BARRIER COATINGS STABILIZED IN THE CUBIC CRYSTALLINE PHASE" (Boutwell et al), Serial No. _____, filed _____, 2003, which is incorporated by reference. The zirconia-containing ceramic compositions used in this upper layer comprise at least about 50 mole % zirconia. Typically, the compositions used in this upper layer comprise from about 50 to about 90 mole % zirconia, more typically from about 60 to about 85 mole % zirconia.

[0019] The zirconia-containing compositions used the upper layer of the thermal barrier coating are capable of being stabilized, typically fully stabilized, in the cubic crystalline phase. To achieve this, these compositions further comprise a stabilizing amount

(up to about 49 mole %) of a stabilizer component. The particular amount of the stabilizer component that is "stabilizing" will depend on a variety of factors, including the thermal insulating properties desired, the particular amounts and types of the stabilizer metal oxides used and like factors. Typically, the stabilizer component comprises from about 5 to about 49 mole %, more typically from about 10 to about 30 mole %, of the composition used in this lower layer.

[0020] The stabilizer component the ceramic composition used in the upper layer at least comprises a first metal oxide selected from the group consisting of ytterbia, neodymia, and mixtures thereof, with or without lanthana, i.e., ytterbia, neodymia, mixtures of ytterbia and neodymia, mixtures of ytterbia and lanthana, mixtures of neodymia and lanthana, and mixtures of ytterbia, neodymia and lanthana. Neodymia has been found to provide the greatest reduction in thermal conductivity as the first metal oxide. Inclusion of ytterbia in the first metal oxide can be desirable because of its higher molecular weight. Inclusion of lanthana in the first metal oxide can create further phonon scattering by effectively increasing lattice strain, provided the amount thereof is relatively low to avoid reducing impact and erosion resistance of the thermal barrier coating. The particular amount of first metal oxide used will depend on a variety of factors, including the thermal insulating properties desired, the particular mixture of first metal oxide(s) used, the stabilizing benefits desired and like factors. The first metal oxide can comprise from about 5 to about 49 mole %, typically from about 10 to about 40 mole %, more typically from about 10 to about 30 mole %, of the ceramic composition used in the upper layer. When included as part of the first metal oxide, lanthana typically comprises from about 1 to about 10 mole %, more typically from about 2 to about 8 mole %, of the composition used in this upper layer.

[0021] The stabilizer component of the ceramic compositions used in the upper layer of the thermal barrier coatings of this invention can also optionally comprise a second metal oxide selected from the group consisting of selected from the group consisting of yttria, calcia, ceria, scandia, magnesia, india and mixtures thereof. This second metal oxide, such as yttria, is one that has been traditionally used to chemically phase-stabilize zirconia-containing ceramic compositions. Typically, this second metal oxide comprises about 4 mole % or less, more typically about 2 mole % or less, of the composition. It has been discovered that the zirconia-containing ceramic compositions of this invention can provide thermal barrier coatings stabilized in the desired cubic crystalline phase without needing to include traditional stabilizers, and in particular traditional stabilizer metal oxides such as yttria, calcia, ceria, scandia, magnesia, or india. Accordingly, the zirconia-containing ceramic

compositions can be substantially free of the second metal oxide, i.e., the second metal oxide can comprise about 0.1 mole % or less of the composition.

[0022] The zirconia-containing ceramic compositions used in the upper layer of the thermal barrier coatings of this invention can also comprise one or more third metal oxides selected from the group consisting of hafnia and tantalum, i.e., tantalum oxide. Inclusion of hafnia increases the molecular weight and C_p of the composition without significantly influencing its stability, thus effectively reducing the thermal conductivity when the zirconia lattice stability is fixed by the stabilizer metal oxide, i.e., the first metal oxide, with or without the second metal oxide. Hafnia inclusion also reduces surface diffusion in the zirconia-containing thermal barrier coating structure during the deposition process, such as physical vapor deposition, used to prepare the thermal barrier coating, as well as during subsequent engine operation due to the lower diffusion rates of hafnia. This results in a more "feathery" structure of the as-deposited coating that contributes to reduced conductivity through increased porosity and reduced density. Inclusion of hafnia also maintains the reduced conductivity of the thermal barrier coating after thermal exposure due to better sintering resistance. Inclusion of tantalum provides oxygen interstitial defects and phonon scattering by mass difference, thus effectively influencing the stability level in the direction opposite that of the other metal oxides, i.e., the first and second metal oxides, while contributing a reduction or lowering of thermal conductivity of the thermal barrier coating.

[0023] The particular amount of hafnia and/or tantalum included will depend on a variety of factors, including the thermal insulating properties desired, the amounts and types of first metal oxide(s) used and like factors. Typically, hafnia is included in an amount of from about 0.5 to about 40 mole %, more typically from about 5 to about 25 mole %, of the ceramic composition used in the upper layer. Typically, tantalum is included in an amount of from about 0.5 to about 10 mole %, more typically from about 2 to about 8 mole %, of the ceramic composition used in this upper layer.

[0024] The improved thermal conductivity properties of the ceramic compositions used to form the upper layer of the thermal barrier coatings of this invention are based on the discovery that, to achieve any further reduction in thermal conductivity beyond that provided by traditional stabilizing metal oxides (e.g., yttria), a different mechanism needs to be used. This mechanism involves including ytterbia and/or neodymia, with or without lanthana, in the stabilizer component, along with hafnia and/or tantalum in these zirconia-containing ceramic compositions. Inclusion of ytterbia and/or neodymia, with or without lanthana, in the stabilizer component, along with hafnia and/or tantalum in these ceramic compositions, imparts

significant benefits to the resulting upper layer of the thermal barrier coating, including one or more of the following: (a) adding atoms of atomic weight higher than zirconium (especially ytterbium, hafnium and tantalum) and typically greater than the atomic weight of the metal atom of first metal oxide (e.g., yttrium) to introduce effective phonon scattering sites and reduce the specific heat of the coating; (b) adding atoms of ionic radius different from zirconium (especially lanthanum and neodymium) and typically with an ionic radius greater than that of the metal atom of first metal oxide (e.g., yttrium) such that the resultant lattice strain introduces phonon scattering sites (i.e., to reduce the phonon mean free path); (c) and adding metal oxides of different valence from zirconia (especially metal oxides of trivalent metal ions such as ytterbia, neodymia, lanthana and yttria and metal oxides of pentavalent metal ions such as tantala) to introduce oxygen defects at a controlled level, thus creating another phonon scattering mechanism.

[0025] The thermal barrier coatings of this invention further comprise a zirconia-containing lower layer wherein the zirconia is stabilized in the tetragonal crystalline phase to improve the adherence of the upper layer to the underlying bond coat layer. The ceramic composition used in the lower layer comprises at least about 80 mole % zirconia. Typically, the ceramic composition used in this lower layer comprises from about 86 to about 97 mole % zirconia, more typically from about 88 to about 95 mole % zirconia.

[0026] The ceramic composition used in this lower layer further comprises a stabilizing amount up to about 10 mole % of the lower layer of a stabilizer component of a first metal oxide and a second metal oxide. The particular amount of the stabilizer component that is "stabilizing" will depend on a variety of factors, including the thermal insulating properties desired, the ability to minimize or reduce sintering of the resultant coating, the particular amounts and types of the first, second and optional third metal oxides used and like factors. Typically, the stabilizer component comprises from about 3 to about 10 mole %, more typically from about 5 to about 8 mole %, of the composition used in this lower layer.

[0027] The first metal oxide can be selected from the group consisting of yttria, calcia, ceria, scandia, magnesia, india and mixtures thereof. The particular amount of the first metal oxide will depend on a variety of factors, including the thermal insulating properties desired, the particular first metal oxide used, the amounts and types of first metal oxide used and like factors. Typically the first metal oxide comprises from about 1.5 to about 6 mole %, more typically from about 3 to about 5 mole %, of the composition. Ceramic compositions of this invention typically comprise yttria as the first metal oxide.

[0028] The second metal oxide can be selected from the group consisting of lanthana, neodymia, ytterbia and mixtures thereof. The particular amount of second metal oxide(s) included will depend on a variety of factors, including the thermal insulating properties desired, the particular second metal oxide(s) used, the amounts and types of first metal oxides used and like factors. Typically the second metal oxide comprises from about 0.5 to about 8.5 mole %, more typically from about 1.5 to about 4 mole % of the ceramic composition used in the lower layer. The ceramic composition of lower layers of this invention typically comprise lanthana, ytterbia or mixtures thereof as the second metal oxide.

[0029] Particularly suitable zirconia-containing ceramic compositions for use in the lower layer are disclosed in copending U.S. nonprovisional applications entitled "CERAMIC COMPOSITIONS FOR LOW CONDUCTIVITY THERMAL BARRIER COATINGS" (Gorman et al), Serial No. _____, filed _____, 2003, which is incorporated by reference. In addition to zirconia and the stabilizer component, these particularly suitable ceramic compositions further comprise hafnia and optionally tantalum. Inclusion of hafnia increases the molecular weight and specific heat of the lower layer without significantly influencing its stability, thus effectively reducing thermal conductivity when the zirconia lattice stability is fixed by the stabilizer metal oxides, i.e., the first and second metal oxides. Hafnia is typically included in an amount of from about 0.5 to about 15 mole % of the ceramic composition used in the lower layer. More typically, hafnia comprises from about 1.5 to about 5 mole % of the ceramic composition used in this lower layer.

[0030] Optional inclusion of tantalum provides oxygen interstitial defects and phonon scattering by mass difference, thus effectively influencing the stability level in the direction opposite that of the stabilizer metal oxides, while contributing a reduction or lowering of thermal conductivity of the thermal barrier coating. Tantalum is typically included in an amount of from about 0.5 to about 1.5 moles %, more typically from about 0.5 to about 1 moles %, of the ceramic composition used in the lower layer.

[0031] Thermal barrier coatings of this invention are useful with a wide variety of turbine engine (e.g., gas turbine engine) parts and components that are formed from substrates, typically metal substrates comprising a variety of metals and metal alloys, including superalloys, and are operated at, or exposed to, high temperatures, especially higher temperatures that occur during normal engine operation. These turbine engine parts and components can include turbine airfoils such as blades and vanes, turbine shrouds, turbine nozzles, combustor components such as liners and deflectors, augmentor hardware of gas turbine engines and the like. The thermal barrier coatings of this invention can also cover a

portion or all of the metal substrate. For example, with regard to airfoils such as blades, the thermal barrier coatings of this invention are typically used to protect, cover or overlay portions of the metal substrate of the airfoil rather than the entire component, e.g., the thermal barrier coatings cover the leading and trailing edges and other surfaces of the airfoil, but not the attachment area. While the following discussion of the thermal barrier coatings of this invention will be with reference to metal substrates of turbine engine parts and components, it should also be understood that the thermal barrier coatings of this invention are useful with metal substrates of other articles that operate at, or are exposed to, high temperatures.

[0032] The various embodiments of the thermal barrier coatings of this invention are further illustrated by reference to the drawings as described hereafter. Referring to the drawings, the FIG. shows a partial side sectional view of an embodiment of the thermal barrier coating used with the metal substrate of an article indicated generally as 10. As shown in the FIG., article 10 has a metal substrate indicated generally as 14. Substrate 14 can comprise any of a variety of metals, or more typically metal alloys, that are typically protected by thermal barrier coatings, including those based on nickel, cobalt and/or iron alloys. For example, substrate 14 can comprise a high temperature, heat-resistant alloy, e.g., a superalloy. Such high temperature alloys are disclosed in various references, such as U.S. Pat. No. 5,399,313 (Ross et al), issued March 21, 1995 and U.S. Pat. No. 4,116,723 (Gell et al), issued September 26, 1978, both of which are incorporated by reference. High temperature alloys are also generally described in Kirk-Othmer's Encyclopedia of Chemical Technology, 3rd Ed., Vol. 12, pp. 417-479 (1980), and Vol. 15, pp. 787-800 (1981). Illustrative high temperature nickel-based alloys are designated by the trade names Inconel®, Nimonic®, Rene® (e.g., Rene® 80, Rene® N5 alloys), and Udiment®. As described above, the type of substrate 14 can vary widely, but it is representatively in the form of a turbine part or component, such as an airfoil (e.g., blade) or turbine shroud.

[0033] As shown in the FIG., article 10 also includes a bond coat layer indicated generally as 18 that is adjacent to and overlies substrate 14. Bond coat layer 18 is typically formed from a metallic oxidation-resistant material that protects the underlying substrate 14 and enables the thermal barrier coating indicated generally as 22 to more tenaciously adhere to substrate 14. Suitable materials for bond coat layer 18 include MCrAlY alloy powders, where M represents a metal such as iron, nickel, platinum or cobalt, or NiAl(Zr) compositions, as well as various noble metal diffusion aluminides such as platinum aluminide, as well as simple aluminides (i.e., those formed without noble metals). This bond coat layer 18 can be applied, deposited or otherwise formed on substrate 10 by any of a

variety of conventional techniques, such as physical vapor deposition (PVD), including electron beam physical vapor deposition (EB-PVD), plasma spray, including air plasma spray (APS) and vacuum plasma spray (VPS), or other thermal spray deposition methods such as high velocity oxy-fuel (HVOF) spray, detonation, or wire spray, chemical vapor deposition (CVD), pack cementation and vapor phase aluminizing in the case of metal diffusion aluminides (see, for example, U.S. Pat. No. 4,148,275 (Benden et al), issued April 10, 1979; U.S. Pat. No. 5,928,725 (Howard et al), issued July 27, 1999; and U.S. Pat. No. 6,039,810 (Mantkowski et al), issued March 21, 2000, all of which are incorporated by reference and which disclose various apparatus and methods for applying diffusion aluminide coatings, or combinations of such techniques, such as, for example, a combination of plasma spray and diffusion aluminide techniques. Typically, plasma spray or diffusion techniques are employed to deposit bond coat layer 18. Usually, the deposited bond coat layer 18 has a thickness in the range of from about 1 to about 20 mils (from about 25 to about 508 microns). For bond coat layers 18 deposited by PVD techniques such as ED-PVD or diffusion aluminide processes, the thickness is more typically in the range of from about 1 to about 4 mils (from about 25 to about 102 microns). For bond coat layers deposited by plasma spray techniques such as APS, the thickness is more typically in the range of from about 3 to about 15 mils (from about 76 to about 381 microns).

[0034] As shown in the FIG., the thermal barrier coating (TBC) 22 prepared of this invention is adjacent to and overlies bond coat layer 18. The thickness of TBC 22 is typically in the range of from about 1 to about 100 mils (from about 25 to about 2540 microns) and will depend upon a variety of factors, including the article 10 that is involved. For example, for turbine shrouds, TBC 22 is typically thicker and is usually in the range of from about 30 to about 70 mils (from about 762 to about 1788 microns), more typically from about 40 to about 60 mils (from about 1016 to about 1524 microns). By contrast, in the case of turbine blades, TBC 22 is typically thinner and is usually in the range of from about 1 to about 30 mils (from about 25 to about 762 microns), more typically from about 3 to about 20 mils (from about 76 to about 508 microns).

[0035] As shown in the FIG., TBC 22 comprises the lower layer (as previously described) indicated as 26 that is adjacent to and overlies bond coat layer 18. This lower layer will usually comprise a minor fraction of TBC 22. Typically, this lower layer 26 comprises from about 5 to about 40%, more typically from about 15 to about 30%, of the thickness of TBC 22. TBC 22 further comprises the upper layer (as previously described) indicated as 30, and is adjacent to and overlies lower layer 26. Upper layer 30 will normally

comprise the majority of the thickness of TBC 22. Typically, upper layer 30 will comprise from about 60 to about 95%, more typically from about 70 to about 85%, of the thickness of TBC 22.

[0036] Referring to the FIG., the lower layer 26 of TBC 22 can be applied, deposited or otherwise formed on bond coat layer 18 by any of a variety of conventional techniques, to be followed by the applying, depositing or otherwise forming of upper layer 30 of TBC 22 on lower layer 26 by any of such techniques. These techniques include physical vapor deposition (PVD), including electron beam physical vapor deposition (EB-PVD), plasma spray, including air plasma spray (APS) and vacuum plasma spray (VPS), or other thermal spray deposition methods such as high velocity oxy-fuel (HVOF) spray, detonation, or wire spray; chemical vapor deposition (CVD), or combinations of plasma spray and CVD techniques. The particular technique used for applying, depositing or otherwise forming layers 26, 30 of TBC 22 will typically depend on the composition of TBC 22, its thickness and especially the physical structure desired for TBC 22. For example, PVD techniques tend to be useful in forming TBCs having a strain-tolerant columnar structure. By contrast, plasma spray techniques (e.g., APS) tend to create a splat-layered porous structure. Layers 26, 30 of TBC 22 are typically formed by PVD, and especially EB-PVD techniques to provide a strain-tolerant columnar structure.

[0037] Various types of PVD and especially EB-PVD techniques well known to those skilled in the art can also be utilized to form layers 26, 30 of TBCs 22. See, for example, U.S. Pat. No. 5,645,893 (Rickerby et al), issued July 8, 1997 (especially col. 3, lines 36-63); U.S. Pat. No. 5,716,720 (Murphy), issued February 10, 1998 (especially col. 5, lines 24-61); and U.S. Pat. No. 6,447,854 (Rigney et al), issued September 10 2002, which are all incorporated by reference. Suitable EB-PVD techniques for use herein typically involve a coating chamber with a gas (or gas mixture) that preferably includes oxygen and an inert gas, though an oxygen-free coating atmosphere can also be employed. The ceramic compositions are then evaporated with an electron beams focused on, for example, ingots of the ceramic coating compositions so as to produce a vapor of metal ions, oxygen ions and one or more metal oxides. The metal and oxygen ions and metal oxides recombine to form layers 26, 30 of TBC 22 on the surface of metal substrate 14, or more typically on bond coat layer 18.

[0038] Various types of plasma-spray techniques well known to those skilled in the art can also be utilized to form layers 26, 30 of TBCs 22. See, for example, Kirk-Othmer Encyclopedia of Chemical Technology, 3rd Ed., Vol. 15, page 255, and references noted therein, as well as U.S. Pat. No. 5,332,598 (Kawasaki et al), issued July 26, 1994; U.S. Pat.

No. 5,047,612 (Savkar et al) issued September 10, 1991; and U.S. Pat. No. 4,741,286 (Itoh et al), issued May 3, 1998 (herein incorporated by reference) which are instructive in regard to various aspects of plasma spraying suitable for use herein. In general, typical plasma spray techniques involve the formation of a high-temperature plasma, which produces a thermal plume. The ceramic coating composition, e.g., ceramic powders, are fed into the plume, and the high-velocity plume is directed toward the bond coat layer 18. Various details of such plasma spray coating techniques will be well-known to those skilled in the art, including various relevant steps and process parameters such as cleaning of the bond coat surface 18 prior to deposition; grit blasting to remove oxides and roughen the surface substrate temperatures, plasma spray parameters such as spray distances (gun-to-substrate), selection of the number of spray-passes, powder feed rates, particle velocity, torch power, plasma gas selection, oxidation control to adjust oxide stoichiometry, angle-of-deposition, post-treatment of the applied coating; and the like. Torch power can vary in the range of about 10 kilowatts to about 200 kilowatts, and in preferred embodiments, ranges from about 40 kilowatts to about 60 kilowatts. The velocity of the ceramic coating composition particles flowing into the plasma plume (or plasma "jet") is another parameter which is usually controlled very closely.

[0039] Suitable plasma spray systems are described in, for example, U.S. Pat. No. 5,047,612 (Savkar et al) issued September 10, 1991, which is incorporated by reference. Briefly, a typical plasma spray system includes a plasma gun anode which has a nozzle pointed in the direction of the deposit-surface of the substrate being coated. The plasma gun is often controlled automatically, e.g., by a robotic mechanism, which is capable of moving the gun in various patterns across the substrate surface. The plasma plume extends in an axial direction between the exit of the plasma gun anode and the substrate surface. Some sort of powder injection means is disposed at a predetermined, desired axial location between the anode and the substrate surface. In some embodiments of such systems, the powder injection means is spaced apart in a radial sense from the plasma plume region, and an injector tube for the powder material is situated in a position so that it can direct the powder into the plasma plume at a desired angle. The powder particles, entrained in a carrier gas, are propelled through the injector and into the plasma plume. The particles are then heated in the plasma and propelled toward the substrate. The particles melt, impact on the substrate, and quickly cool to form the thermal barrier coating.

EXAMPLES

[0040] The following illustrates embodiments of thermal barrier coatings of this invention:

Example 1:

The lower layer 26 of TBC 22 can be formed as a stabilized tetragonal crystalline phase on bond coat layer 18 by EB-PVD techniques from any of the ceramic compositions shown in Tables 1 and 2:

Table 1

Metal Oxide	Mole %	Wt. %
Zirconia	93.7	86.7
Yttria	1.5	2.5
Ytterbia	1.9	5.8
Lanthana	0.5	1.5
Hafnia	2.2	3.5

Table 2

Metal Oxide	Mole %	Wt. %
Zirconia	92.2	85.0
Yttria	1.8	3.0
Ytterbia	1.0	3.0
Lanthana	1.2	3.0
Hafnia	3.8	6.0

The upper layer 30 of the TBC 22 can be formed by EB-PVD, APS or any other suitable technique from any of the ceramic composition shown in Tables 3-5 as a stabilized cubic crystalline phase on any of these layers 26:

Table 3

Metal Oxide	Mole %	Wt. %
Zirconia	61	40
Ytterbia	17	35
Hafnia	22	25

Table 4

Metal Oxide	Mole %	Wt. %
Zirconia	61	40
Ytterbia	10	20
Neodymia	11	20
Hafnia	18	20

Table 5

Metal Oxide	Mole %	Wt. %
Zirconia	71	54
Ytterbia	13	30
Lanthana	3	6
Hafnia	8	10

Example 2:

A TBC 22 can be prepared by EB-PVD techniques by first depositing the ceramic composition shown in Table 6 on bond coat layer 18 to provide lower layer 26 stabilized in the tetragonal crystalline phase and then depositing the ceramic composition shown in Table 7 on lower layer 26 to provide upper layer 30 stabilized in the cubic crystalline phase:

Table 6 (Lower Layer)

Metal Oxide	Mole %	Wt. %
Zirconia	94.1	87.8
Yttria	4.1	7.0
Ytterbia	1.8	5.2

Table 7 (Upper Layer)

Metal Oxide	Mole %	Wt. %
Zirconia	74.7	48.3
Yttria	3.7	7.0
Ytterbia	20.8	43.8
Hafnia	0.8	0.9

Example 3:

A TBC 22 can be prepared by EB-PVD techniques by first depositing the ceramic composition shown in Table 8 on bond coat layer 18 to provide lower layer 26 stabilized in the tetragonal crystalline phase, and then depositing the ceramic composition shown in Table 7 on lower layer 26 to provide upper layer 30 stabilized in the cubic crystalline phase:

Table 8 (Lower Layer)

Metal Oxide	Mole %	Wt. %
Zirconia	94.0	88.4
Yttria	4.1	7.0
Lanthana	1.9	4.6

Table 9 (Upper Layer)

Metal Oxide	Mole %	Wt. %
Zirconia	61.3	40.0
Ytterbia	9.6	20.0
Neodymia	11.2	20.0
Hafnia	17.9	20.0

[0041] While specific embodiments of this invention have been described, it will be apparent to those skilled in the art that various modifications thereto can be made without departing from the spirit and scope of this invention as defined in the appended claims.